Study of 3D Waveguide Silicon Optical Interposer Technology for Highly-integrated Photonic System

著者	開 達郎
number	62
学位授与機関	Tohoku University
学位授与番号	工博第5433号
URL	http://hdl.handle.net/10097/00124753

	ひらき　たつろう
氏　　　　　　名	開　達　郎
授　与　学　位	博士（工学）
学位授与年月日	平成２９年９月２５日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）バイオロボティクス専攻
学位論文題目	Study of 3D Waveguide Silicon Optical Interposer Technology for Highly-integrated Photonic System (高集積フォトニックシステム用三次元導波路型シリコン光インターポーザ技術の研究)
指　導　教　員	東北大学教授　田中　徹
論文審査委員	主査　東北大学教授　田中　徹　東北大学教授　小野　崇人　東北大学教授　羽根　一博

論 文 内 容 要 旨

With a rapid increase of floating point number operations per second (FLOPS) of a computer system, its performance is limited by not only the scaling of the transistor but also the input/output (I/O) bandwidth of the interconnections. The required I/O bandwidth will be more than 100 Tb/s–1 Pb/s to maintain 1 B/FLOPS, but such a high capacity transmission cannot be achieved by using conventional copper interconnections. An optical interconnection is a promising solution to overcome the performance limit. In order to implement it in chip-to-chip interconnections, the key technology is silicon (Si) photonics, which enables the fabrication of compact optical components, such as modulators and photo detectors, by using the complementary metal-oxide-semiconductor (CMOS) fabrication process. Using this technology, a Si optical interposer has already been demonstrated as an optical I/O of the computer system. However, the bandwidths of the modulators and receivers are not sufficient to satisfy petabit-class transmission capacity. Therefore, an optical signal multiplexing such as wavelength-division multiplexing (WDM) is also required. In the Si optical interposer, the number of WDM channels is typically limited by the crosstalk of the WDM multiplexer/demultiplexer (MUX/DEMUX) constructed by Si waveguides. The fundamental hurdle is a phase error of the Si nanowire waveguide owing to the fabrication error. The required number of channels (512) for the peta-bit class transmission cannot be achieved using WDM channels only therefore an additional degree of freedom of the orthogonal optical channels is necessary.

This study focuses on implementing additional multiplexed channels using mode division multiplexing in the Si optical interposer. The higher-order modes in multimode fibers can be used as an additional orthogonal optical channel; therefore, the signal multiplicity can be more than 512 channels by combining with WDM signals. In Chapter 2, the fundamental issues of the conventional mode and wavelength MUX/DEMUXs on Si platform are described. For the mode MUX/DEMUX in the Si interposer, a critical issue is the mode field mismatch between the planar Si waveguide cores and higher-order modes in the multimode fiber. For example, a higher-order fiber mode such as LP_{11b} mode cannot be coupled to the conventional planar Si nanowire waveguide using butt coupling. Moreover, for the wavelength MUX/DEMUX, the Si waveguide has a large thermo-optic (TO) coefficient; therefore, the central wavelength shift of the Si WDM filter owing to temperature variations is very large. These problems limit the number of channels in mode- and wavelength-division multiplexing in the Si optical interposer. To overcome these problems, this study proposed a three-dimensional (3D)-waveguide structure with different material properties, such as refractive index and TO coefficients. This scheme enables mode-field matching between the waveguide in the Si interposer and multimode fiber, and compensates for the TO effects in the WDM filters. Consequently, petabit-class transmission capacity is achieved in the Si optical interposer. This study addresses the details of mode and wavelength MUX/DEMUXs and their integration.

In Chapter 3, the mode MUX/DEMUX on Si platform is proposed by introducing 3D waveguides. Using the butt coupling of the 3D waveguide to the multimode fiber, the field patterns in eigenmodes of the 3D waveguide almost match those of various higher-order fiber modes, including LP_{11b} mode. As a key feature of the design, the intensity profile of the 3D-waveguide is tuned by designing the refractive index and the width of each core. With different refractive-index cores in the stacked cores, the mode intensity profiles are changed from the fiber-matching patterns to the nearly single-mode patterns by adiabatically changing each core width in the tapered waveguide. This scheme enables the 3D waveguide to be coupled to the higher-order modes of the multimode fiber, and optically MUX/DEMUX different single-mode waveguides. Consequently, the optical mode MUX/DEMUX with more than three LP modes can be realized in the Si optical interposer. In order to construct the designed 3D waveguide, additional core materials, whose refractive index can be controlled, are required. A promising solution is Si-rich silica (SiO_x) based core, whose refractive index ranges from 1.47 to 1.7 by changing the atomic composition of Si and oxygen. It is suitable because it can be deposited using a low temperature process at approximately 200 °C, and thus it is applicable to the back-end on line (BEOL) process. Using the stacked SiOx cores, a three-mode MUX/DEMUX was fabricated on the Si platform. The fabrication process flow is as follows. First, a lower-layer SiO_x core film, whose refractive index was 1.50, was formed on a thermal oxide of a Si substrate by using electron-cyclotron resonance (ECR) PE-CVD at 200 °C. Subsequently, a lower-layer SiO_x film was patterned followed by the deposition of an overcladding film. Subsequently, the overcladding film was flattened using chemical-mechanical polishing during which the inter-layer thickness was controlled to be 2.0 μm. After that, an upper-layer SiOx core, whose refractive index was 1.49, was formed and patterned at less than 200 °C and a 4-μm-thick overcladding film was finally deposited. The fabricated device experimentally performed three-mode DEMUX (LP_{01}, LP_{11a}, LP_{11b} modes) with a mode selectivity of more than 6.5 dB at 1550 nm. The polarization dependence of the device is theoretically small therefore, using both the transverse electric and magnetic modes, the total mode multiplicity can be six, which is sufficiently large for petabit-class transmission.

In Chapter 4, an atherrmal wavelength filter in the Si optical interposer is proposed. The key feature is the construction of a delay-line interferometer (DLI) with Si and SiN waveguides that have different TO coefficients. This configuration enables to balance the TO effects in the two waveguides in the DLI. Notably, it enables a larger fabrication tolerance than that of the other design, which controls the TO coefficients of the DLI with changing the widths of the Si waveguides. For example, when using the 440-nm-wide Si waveguide and the 800-nm-wide SiN waveguide, $d\lambda/dT$ of the DLI could be less than 0.1 pm/K by using a state-of-the-art fabrication process. This $d\lambda/dT$ is more than ten times smaller than that obtained by controlling the TO coefficients with changing the widths of the Si waveguides. Furthermore, $d\lambda/dT$ less than 0.1 pm/K is sufficiently low to suppress the interchannel crosstalk and power penalty of the wavelength MUX/DEMUX with a temperature shift of 100 °C. Therefore, this configuration is suitable for a petabit-class optical interposer. The proposed DLI was fabricated on an 8-inch silicon-on-insulator wafer. The Si waveguides were first patterned and subsequently a clad film was deposited. Subsequently, the clad film was flattened, and then SiN waveguide cores were formed. The inter-layer clad thickness between the Si and SiN waveguides was controlled to be 100 nm. Finally, an overclad film was deposited. The fabricated DLI exhibited $d\lambda/dT$ of −2.8 pm/K, which was more than 20 times smaller than that of the conventional Si-waveguide DLI. The measured temperature sensitivity was sufficiently low to realize the required channel spacing of 100 GHz. Although $d\lambda/dT$ of the Si-SiN DLI was larger than the ideal case (< 0.1 pm/K) owing to the large fabrication error, the measured result was still better than those of DLIs with other design using wide and narrow Si waveguides (~5 pm/K). The small temperature sensitivity of the fabricated device was also evaluated by measuring the eye diagram. The eye diagram using the Si-SiN DLI wavelength filter was clearly open at a temperature change of 4 K, whereas that of the Si-waveguide was completely closed at a temperature change of only 1 K. Moreover, to reduce the loss of the proposed athermal wavelength filter, a novel method to deposit the SiN film was proposed using a hydrogen-free gas source. It removes the residual N-H bonds, which has a large absorption peak in the C band, in the SiN film. The fabricated hydrogen-free SiN waveguides showed 0.55 dB/cm in the C band, which was further smaller than that of the conventional SiN waveguide. This technology can be applied to the proposed wavelength filters, and thus it is a promising solution to increase the wavelength multiplicity of a Si optical interposer.

In Chapter 5, the integration technology of the proposed 3D waveguide mode and wavelength MUX/DEMUXs with Si/Ge active devices is described. There are two main issues: one is the reduction of the loss and size of the inter-layer coupling between the stacked SiO_x waveguides to connect the mode MUX/DEMUX to the Si/Ge active devices, and the other is the monolithic integration with a high-speed Ge photodetector (PD) using a CMOS-compatible process.

First, a vertical directional coupler was designed and fabricated to realize a compact inter-layer coupling between the stacked SiO_x waveguides with low loss. In order to demonstrate the feasibility of the loss-less vertical directional coupler, an impedance-matched coupler was fabricated with two SiO_x layers. In this study, it was designed with the same refractive indices (1.505) of the cores in the two layers, whereas those of the overclad (1.46) and undercladding (1.444) films are different. The inter-layer clad thickness and each core thickness were 1.0 and 3.0 μm, respectively. The measured coupling efficiency between the stacked SiO_x waveguides was almost 100% with a coupling length of 230 μm, which was almost consistent with the calculation. At a wavelength of 1543.4 nm, the estimated coupling losses were less than 0.1 dB in both the TE and TM modes. This scheme is beneficial to construct a compact and low-loss inter-layer coupler on the Si optical interposer.

Subsequently, a novel Ge PD with n-type Si layer was proposed to realize the monolithic integration of the 3D waveguide device with a high-speed Ge PD. As features, the Si layer on the n-type Ge surface prevents the damages to Ge in the CMOS process, and enables the small contact resistance between the n-Ge and metal. In order to verify the feasibility, the proposed Ge PD with SiO_x waveguide was designed and fabricated. In this work, a 16-channel Ge PD array was successfully fabricated without process damages in the PDs using the CMOS compatible process. The fabricated PD exhibits a sufficiently low resistance to operate at non-return-to-zero (NRZ) 25 Gbit/s. For a feasibility check, the eye diagram at NRZ 25 Gbit/s was measured using the stand-alone Ge PD with applied DC bias of 1.0 V. The eye diagram was clearly open at 25 Gbit/s signals. In the illuminated state, by subtracting the optical losses of the fiber coupling, spot-size converter, and Si waveguides from the input light power, the responsivity of the fabricated Ge PD was determined to be approximately 1.1 A/W. The responsivity was not degraded by the n-Si contact film. Moreover, the measured relationships between the photo current and wavelength in the C band shows flat characteristics. The fabricated PD is suitable to be used for the WDM transmission because of the high responsivity in the entire C band. In order to verify the feasibility of the WDM receiver operation, a DEMUX operation was also demonstrated with the fabricated 16-ch Ge PD arrays with SiO_x waveguides. Here, the wavelength DEMUX was constructed by the SiOx-waveguide arrayed-waveguide grating. The WDM DEMUX in the entire C band and 16 × 22 Gbit/s DEMUX were successfully achieved. This indicates that all of the integrated 16-ch Ge PDs were not degraded by the CMOS fabrication process. These technologies enable the monolithic integration of the 3D waveguide mode and wavelength MUX/DEMUX with high-speed active devices by using the CMOS fabrication technology.

Consequently, all the elements of a petabit-class Si optical interposer were successfully developed. Using these technologies, the performance of the computer system can be sustainably improved in the future.

論文審査結果の要旨

飛躍的な進歩を続ける半導体集積回路(LSI)技術は，コンピュータ性能の持続的発展を支え，今日の超高度情報化社会をもたらした。従来，コンピュータ性能の向上は主にトランジスタの微細化によって達成されてきたが，近年は金属配線の伝送容量がボトルネックとなって高性能化が阻害されている。現在，コンピュータ性能の持続的発展を達成するために，金属配線の伝送容量限界を突破する新たな配線技術が要求されている。この要求を満たす技術として，光配線技術が有望である。光信号は高速変調信号伝送と超高密度多重が可能であり，従来の金属配線の伝送容量限界を突破することが期待できる。この大伝送容量光配線を実現するためには，LSI 用の Si-CMOS プロセスを用いて小型かつ低コストな光送受信器チップ(Si 光インターポーザ)を作製することが必要である。特に，超高密度光信号多重に向けて，波長及びファイバモードを多重化できる Si チップ上光合分波器の作製が必須である。本論文は，従来の平面光波回路を用いる Si 光インターポーザでは困難な超高密度光信号多重を実現するため，Si 以外の導波路コア材料を用いた高多重・温度無依存の三次元導波路型 Si 光インターポーザについて研究したもので，全編 6 章からなる。

第 1 章は序論であり，本研究の背景，目的，及び構成を述べている。

第 2 章では，従来の平面光波回路を用いる Si 光インターポーザの課題であるファイバモードの多重化限界と波長合分波器の温度依存性について述べ，これらの課題を解決する手段として，高多重・温度無依存の三次元導波路型 Si 光インターポーザを提案している。これは工学的に重要な知見である。

第 3 章では，従来の平面光波回路を用いる Si 光インターポーザでは実現困難な 3 つのファイバモードの合分波に向けて，Si 基板と垂直方向の設計自由度に着目し，Si-CMOS バックエンドプロセスを用いて Si チップ上に三次元石英系導波路構造を作製する技術を世界に先駆けて確立している。この技術を用いて 3 つのファイバモード分布と整合可能な 3 モード合分波器を設計・作製し，モード選択性 6.4dB 以上の 3 モード合分波器の実現に成功している。これらは工学上重要な成果である。

第4章では，従来の平面光波回路を用いる Si 光インターポーザでは実現困難な波長合分波器の温度無依存化に向けて，Si とは異なる熱光学係数を有する材料である窒化シリコン(SiN)導波路を Si チップ上に積層し，Si 及び SiN 導波路を用いた温度無依存波長フィルタを新たに提案している。Si-CMOS と親和性のある導波路積層プロセスを用いて波長フィルタを作製し，Si 導波路コアのみを用いている平面光波回路では実現困難な低波長依存(-2.8pm/K)を世界で初めて達成している。本成果は，温度変化が顕著な LSI への応用における重要課題である動作波長シフトを大幅に低減するものであり，光配線技術における高密度波長多重の実用化に向けた重要な成果である。

第 5 章では，前章までに述べた三次元導波路型モード/波長合分波器を Si 光インターポーザ上に集積する技術として，三次元導波路間の光結合器とゲルマニウム(Ge)受光器の集積技術に関して述べている。三次元導波路間の光結合器として，積層した SiOx 導波路の方向性結合器を提案し，300µm以下のサイズで光損失がない層間光結合器を初めて実現している。また，Ge 受光器との一体集積のために，Si-CMOS プロセスによる Ge へのダメージ防止と Ge のコンタクト抵抗低減の両立を可能にする集積プロセス構築に成功している。この技術を用いて，SiOx 導波路と Ge 受光器の一体集積を行い，16 チャンネル WDM 受信に成功しており、三次元導波路型 Si 光インターポーザの実用化に向けた重要な成果である。

第 6 章は結論である。

以上要するに，本論文は，従来の金属配線の伝送容量限界を突破する新たな LSI 用光配線を用いた高集積フォトニックシステムの実現を目的に，1) Si チップ上に三次元石英系導波路構造を作製して 3 つのファイバモードの合分波を可能にする技術，2) Si と異なる熱光学係数を有する SiN 導波路を Si チップ上に積層して温度無依存波長フィルタを作製する技術，3) 三次元導波路型モード/波長合分波器を三次元導波路間光結合器及び Ge 受光器と一体集積する技術を開発したもので，高多重・温度無依存の三次元導波路型 Si 光インターポーザの実用化を大きく推進する成果であり，バイオロボティクスおよびシリコンフォトニクスの発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。